QuikSCAT and TRMM Reveal the Interplay Between Dynamic and Hydrologic Parameters in Hurricane Floyd

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Over the ocean, in situ observations in a hurricane are extremely sparse, and conventional satellite data provide only cloud imagery at the top of the storm. Hurricanes are devastating when accompanied by strong winds and heavy rain. Two new satellite missions: QuikSCAT and Tropical Rain Measuring Mission (TRMM), provide the opportunity to observe both wind and rain in hurricanes before landfall. The coincident measurements of surface wind and rain reveal the interplay between the dynamics and the hydrologic balances of the storms. The high spatial resolution of ocean surface winds measured by QuikSCAT improves the computation of the moisture transport, the vertical profiles of moisture sink and diabatic heating, and the difference between evaporation and rain-rate at the surface, for Hurricane Floyd. The results were validated by the observations of surface rain and rain profiles by TRMM. The close relation between the dynamic and hydrologic parameters is visible in Fig. 1 as Hurricane Floyd approaches the Bahamas on 13 September 1999. Surface winds feed moisture into the hurricane. The moisture turns into rain, releases latent heat, and fuels the storm. After the image in Fig. 1 was taken, Hurricane Floyd turned north. Its strength and proximity to the Atlantic coast of the U.S. caused the largest evacuation of citizens in U.S. history. Its landfall on September 16 resulted in severe flooding and devastation in the Carolinas.

A scatterometer sends microwave pulses to the Earth's surface and measures the backscatter power from the surface roughness. Over the ocean, the backscatter is largely due to small

(centimeter) waves on the surface, which are believed to be in equilibrium with the local wind stress. The backscatter power depends not only on the magnitude of the wind stress but also on the wind direction relative to the direction of the radar beam. The capability of measuring wind speed and direction, under both clear and cloudy conditions, is the major uniqueness of the scatterometer. QuikSCAT was launched by the National Aeronautics and Space Administration (NASA) in June 1999 with a radar scatterometer, SeaWinds, on board [Graf et al., 1998]. SeaWinds provides a continuous 1800-km swath, thus providing over 92% coverage of the global ocean daily. The standard wind products have a 25-km resolution, but the data used in this study is specially produced to have a space resolution of 12.5 km. This is significant improvement over previous scatterometers in monitoring hurricanes. The NASA Scatterometer (NSCAT), which failed in 1997, had a wide nadir-gap between two 600-km swaths, one on each side of the spacecraft and a spatial resolution of 25 km; the data gap may prevent full coverage of a hurricane [e.g., Liu et al., 1997]. The scatterometers of European Remote Sensing (ERS) satellites, which have been in operation since 1992, have only a single 479-km swath and a spatial resolution of 50 km.

TRMM is joint mission by NASA and the National Space development Agency (NASDA) of Japan. It was launched in November 1997, with a microwave imager (TMI) and a precipitation radar (PR) on board [Kummerow et al., 1998]. TMI measures radiance from 10.7 to 85 GHz from which a suite of parameters can be derived, including the surface rainfall over oceans. The spatial resolution varies with frequency, starting at 45 km at 10 GHz to 5 km at 85 GHz. PR sends radar pulses and measures the backscatter, giving TRMM the unique capability of measuring the 3-dimensional rainfall distribution over both land and ocean. The horizontal resolution is 4.3 km. The low-inclination orbit of TRMM is designed to give optimal sampling rate for monitoring rainfall.

The dynamic parameter, wind, and the hydrologic parameter, rain, are related by the principle of water and mass conservation. The influence of the ocean surface winds is not confined to the surface, but is felt throughout the atmospheric column. The vertical velocity in pressure coordinate at a certain level is the integral of the wind divergence at that level and all the levels

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below; it governs the vertical component of moisture transport. The apparent 'moisture sink' (Q) at each level, is the difference between condensation and evaporation per unit mass of air, and is a function of the moisture transport at that level [e.g., Yanai et al. 1973]. In convective areas, the vertical transport is particularly important, and the accuracy of surface winds affects the hydrologic balance at all levels. The profile of Q is usually expressed as the profile of diabatic heating rate per unit mass of air, H=LQ/c, where c is the isobaric specific heat and L is the latent heat of vaporization. The vertical integration of Q gives the fresh water flux (F), which is the difference between evaporation (E) and rain rate (R) at the surface [e.g., Bryan and Oort, 1984].

The traditional computation of the heating profiles and the hydrologic forcing on the ocean, uses wind and humidity profiles from rawinsonde. Over the ocean, rawinsonde data are sparse and products from operational numerical weather prediction (NWP) models are used. Provided that the variation of E is small compared with R, the horizontal pattern of F and vertical pattern of H should be comparable to the surface rain pattern and vertical rain profiles measured by TRMM. By adding a wind field from the scatterometer on ERS-1, Hsu et al. [1997] improved the computation of F, using the three-dimensional NWP data of the European Center of Medium Range Weather Forecast (ECMWF), in a convective region in the western tropical Pacific. SeaWinds provides far superior coverage and resolution in describing the surface wind divergence in a hurricane than the ERS-1 scatterometer. The global ECMWF data used by Hsu et al.[1997] have 2.5° latitude by 2.5° longitude (roughly 250 km) spatial resolution and are obviously inadequate to resolve small marine convective systems.

Fig. 2a shows that even with the high resolution of regional mesoscale NWP products, NWP data cannot produce realistic rain patterns for Hurricane Floyd. As demonstrated by the TMI data in Fig. 1, Floyd has double rain bands, but the rain bands are absent in the NWP data. The NWP data are produced operationally by the Eta Data Assimilation System (EDAS) of the National

Center of Environmental Prediction (NCEP). They have 40-km horizontal resolution and cover the whole U.S. mainland and the surrounding nearby oceans.

By simply replacing the wind divergence between 1000 and 975 mb of the EDAS data with the divergence of scatterometer winds in the computation of F, the pattern of F, shown in Fig. 2b, becomes much more realistic with the appearance of more than one spiral rain band which are observed by both TMI (Fig. 1) and by PR (Fig. 2c). Because Hurricane Floyd moves, EDAS data were linearly interpolated to the time of QuikSCAT overpass at 10:48 UT, with the spatial coordinate moving with the eye of the hurricane. At 10:48 UT, the eye of the hurricane is at 71.08°W and 23.82°N, according to the minimum value of backscatter measured by SeaWinds. The location is consistent with the best-track analysis reported by the National Hurricane Center.

Fig. 2c shows that PR, with a swath width of 220 km, has less coverage than the TMI swath, which is 760 km. Although there are differences between surface rain observed by TMI and PR in intensity and distribution, the double circular rain bands are obvious in both. The TRMM overpass is at 9:30 a.m., earlier than SeaWinds, and the eye of Floyd is located slightly to the east. PR provides the instant rain rate integrated over a certain atmospheric layer; vertical distribution of this rain rate should be in qualitative agreement with Q or H.

The vertical sections also show that EDAS data alone obviously do not resolve the eye nor the rain bands of the hurricane (Fig. 2d). With SeaWinds data, two sharp walls of precipitation define the eye of the hurricane at 71.1° (Fig. 2e). The outer rain band passing 70.1 and 71.7° are clearly visible. The addition of scatterometer winds also increases the heating rate aloft. PR data (Fig. 2f) show the eye of Floyd at 70.9°, slightly to the east of EDAS data; the walls of the two circular rain bands are also clearly visible. PR shows a sharp cut off of precipitation at 5 km

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(Fig. 2f) which may represent the freezing level. Although most of the rain is confined to below 5 km in Fig. 2e, the cut off is not as dramatic.

Although the winds produced by the standard SeaWinds geophysical model function meet the accuracy specification in general, the accuracy under the strong wind and high precipitation conditions of a hurricane is uncertain, due to the small validation database. Discarding data with the rain flags provided with the standard data products will eliminate most of data in the hurricane. An semi-empirical correction algorithm. which depends on wind speed and rain-rate. was developed using collocated backscatter measurements by SeaWinds and rain measurements by the Special Sensor Microwave imager for 7 Atlantic hurricanes in 1999. This correction is applied to produce the data set used in this study. The maximum scatterometer wind speed of Floyd (Fig. 1) is found to be about 60 m/s and is comparable to a value of 69.4 m/s reported by the National Hurricane Center. There are, however, still directional errors, easily identifiable in Fig. 1, which may be caused by rain contamination. There are also continuous efforts in validation and algorithm improvement for TRMM.

This study shows that surface wind divergence has strong influence in the hydrologic and energy balances in a hurricane. Four-dimensional assimilation of QuikSCAT and TRMM data into hurricane models in the near future will improve the interpretation of the relation and the prediction hurricane path. The potential of the microwave sensors for early detection of hurricanes by identification of surface close circulation, before they can be recognized in cloud motions observed from conventional weather satellites (K.B. Katsaros, personal communication, 1999), should be explored. Synergistic applications of QuikSCAT and TRMM will contribute to our understanding of marine weather systems. Evolving marine weather system can be monitored through the Seaflux website (http://airsea-www.jpl.nasa.gov/seaflux) which displays

and provides access to near-real time and uniformly gridded QuikSCAT winds every 12 hours. Seaflux also includes TRMM rainfall in near real time for selected storms.

Acknowledgment

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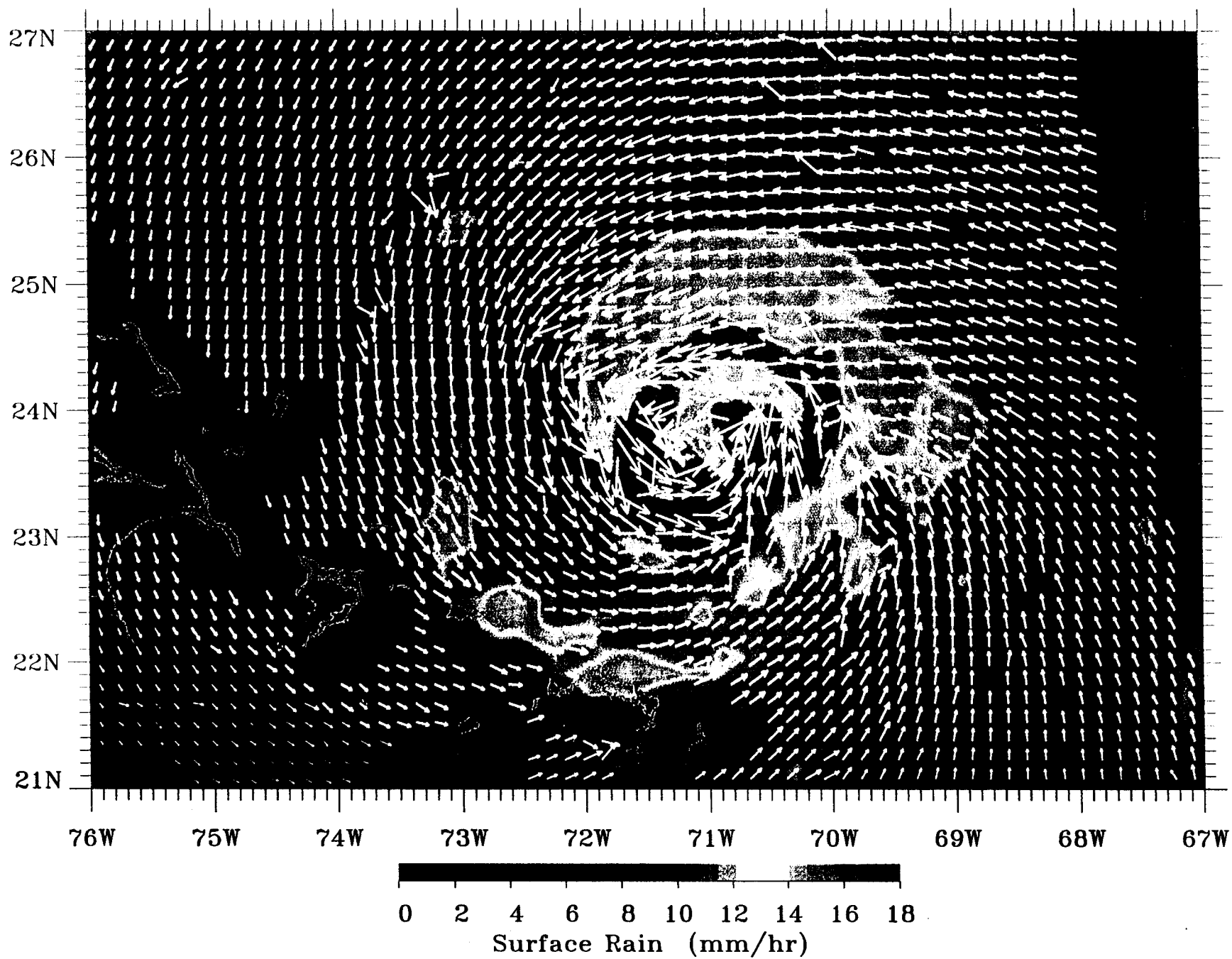
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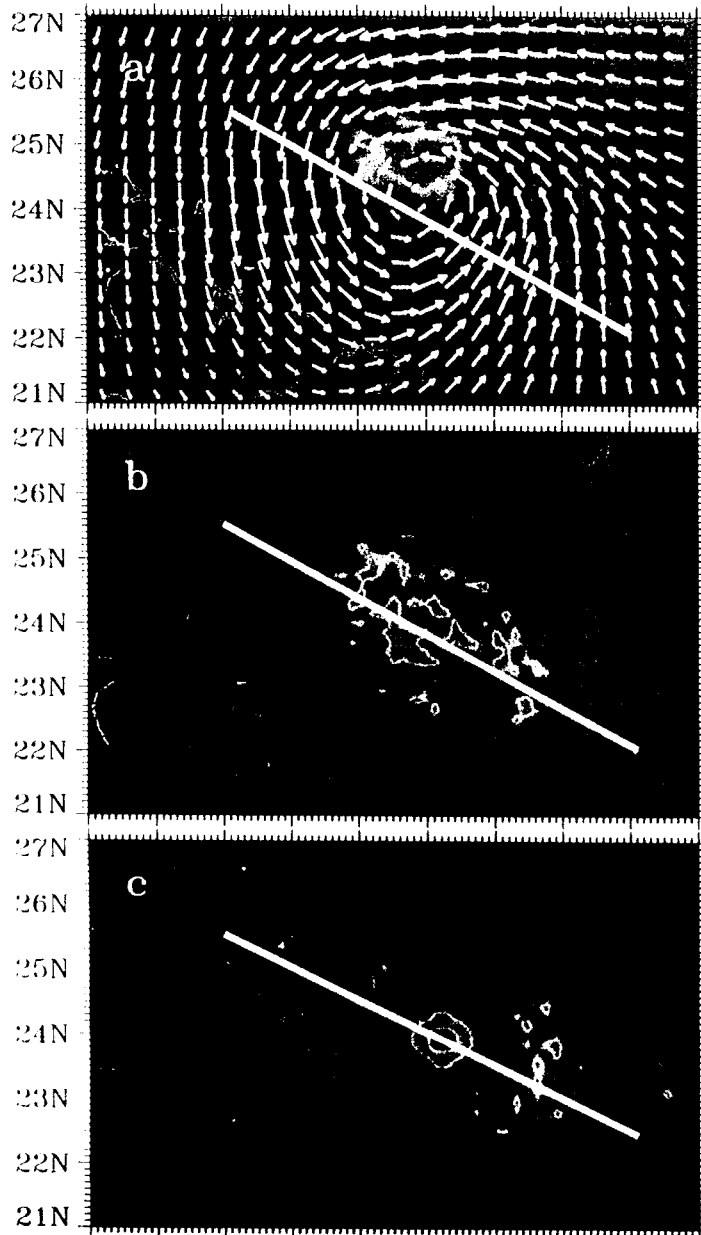
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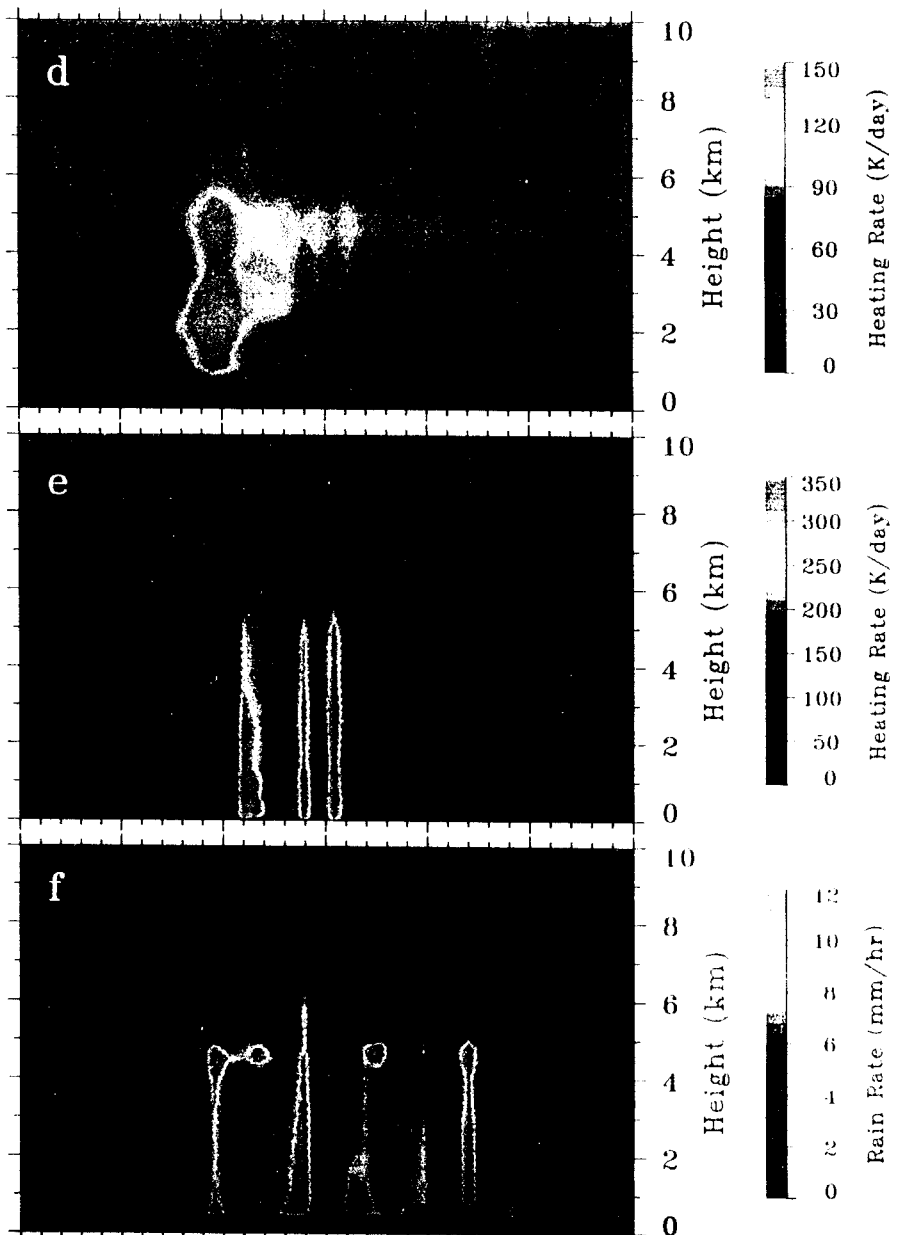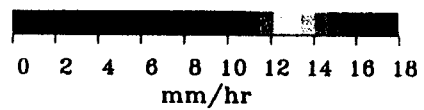
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Fig. 1 Hurricane Floyd is revealed by wind vectors (white arrows) from SeaWinds and surface precipitation (color image) from TMI on 13 September 1999, along the ground-tracks of QuikSCAT and TRMM, which are approximately 78 minutes apart.

Fig. 2 Hurricane Floyd, (a) as revealed by EDAS data interpolated to 10:48 UT, with white arrows representing winds at 1000 mb and the color image represents the computed surface fresh water flux; (b) as surface fresh water flux computed by replacing the surface wind divergence of EDAS data with SeaWinds data which are measured at 10:48 UT; (c) as surface rainfall estimated through a combination of TMI and PR data at 9:30 UT. Vertical profiles of heating and rain rates along white lines in panel (a), (b) and (c) are shown in panels (d), (e) and (f) respectively.

Surface Rain (mm/hr)

Figure panels labeled a, b, c (left column) and d, e, f (right column).

Left column axes: Latitude (21N–27N) vs Longitude (67W–76W).
Color bar (panels a–c): 0 2 4 6 8 10 12 14 16 18 mm/hr

Right column axes: Height (km) 0–10 vs Longitude (68W–74W) (deg).

Panel d color bar: Heating Rate (K/day) 0 30 60 90 120 150
Panel e color bar: Heating Rate (K/day) 0 50 100 150 200 250 300 350
Panel f color bar: Rain Rate (mm/hr) 0 2 4 6 8 10 12